FINAL Copy

MODELING AND PROJECT DEVELOPMENT

D. B. Smith
Jet Propulsion Laboratory, California Institute of Technology

L. J. Koenig, Ph.D.

Abstract

In order to reduce the costs of projects, it is necessary to make full use of today's modern simulation tools. Properly used, simulation tools can enhance the process of a project, reducing cycle time and cost.

By first identifying the key processes of a project, one can then achieve more concurrency by introducing simulation or models of the development to provide the cross communication required for concurrency.

It is the purpose of this paper to show that ten fundamental principles, properly applied, can provide the necessary glue to enable faster, better, and cheaper product development. These principles integrate people, process and tools in order to optimize value to the customer.

Introducing simulation to the development process requires a careful strategy of keeping man-in-the-loop within the process. This interaction requires methods of skillful team development. Future interaction of teams employing this approach is discussed.

Next, the paper describes an analytical study of a Mercury Orbital mission where this method was applied. The study demonstrated a 25-30% reduction in costs. Cycle time was reduced from 48 months to 33 months, a reduction of about the same amount.

Finally, the paper discusses the possibilities of this approach over more technical or complex missions and growth to further reductions in cycle time. The latter discussion will set the context for NASA's new ISE venture.

Introduction

An earlier paper, "Reengineering Space Projects" (ref. 1), first presented the fundamental ideas behind JPL's move to a process-centered organization. This paper presents the concepts behind this move and points out the key principles in the development of people, processes, and technology (models). New ideas are presented which integrate these three entities into a triad referred to as PPT. It will be shown that the order of the triad, people first, is important to development of new sociotechnical systems (STS).

The initial interventions at JPL, and, thus, the initial paper, failed to take into account important organizational development factors, which are crucial to fostering further technical advancement. Identification of variables key to desired outcomes and their ongoing measurement is essential to taking the next steps toward true collaborative engineering with extensive use of models.

This paper develops the case for first assessing the organization before intervening to change it. This paper uses JPL as an example of a typical aerospace organization: a system. JPL has undergone much change over the last fifteen years. The assessment describes these changes as amenable to force-field analysis (ref. 2) and examines the resultant of opposing forces which produced change in the approach to mission development following Voyager, Galileo, and Cassini.

The Mars Pathfinder mission introduced a change toward "Faster, Better, Cheaper" (FBC). JPL moved to a process-centered organization to permanently capture these new development concepts and introduced object technology via model-based design (ref. 3). Development changes are discussed in a simple systems model, which is used to illustrate the interactions of key effects of management and company investment.

Hammer (ref. 4) pointed out the necessity of moving toward a process-based organization. Simple processes are the key to complex problems, and our future space missions are, indeed, more difficult. JPL introduced the following four major processes: 1) management (PLP), 2) mission and system design (MSD), 3) design, build, assemble and test (DBAT), and 4) verify, integrate, validate and operate (VIVO). All of aerospace performs these basic processes in some form during mission development.

Organizing work into four basic processes and eliminating unnecessary steps yields more efficient production capability. The case cited in the Paris paper, the Joint Strike Fighter study conducted by the Navy (ref. 5), illustrates the potential savings from process change when coupled with technology.

With the requirement to change, the potential of process, and the precedence set by Pathfinder, the stage is set for reengineering JPL. However, making the necessary changes requires an understanding of the organizational culture. Earlier attempts to effect change were unsuccessful without this understanding. This paper describes JPL's culture in term of Schneider's model (ref. 6) and implies the need for more interdependence to enable the design and launch of many smaller missions to replace the larger Cassini-like missions.

Introduction of parallel structures (ref. 7), such as Team X, which saved NASA approximately eight million dollars in 1996, can work because they use existing culture, rather than attempt to change it. Insights gained by observing this permanent parallel structure within JPL's culture will enable future parallel structures to effect change within the other processes.

With an understanding of the system model and the role of parallel structures, as well as the importance of cultural assessment, the paper proposes ten essential principles to guide development toward model-based system design. The principles are fundamental to the triad. Application of the triad is discussed in terms of future parallel structures and their interactions. The concept of Team X implies a Team Y and other teams integral to the concept of teams of teams. These teams' interactions form new parallel structures within processes, which are permanent (rather than the temporary ones described in ref. 8). They are necessary to blend the processes into a coherent, efficient, interactive system.

Application of these principles to a conceptual Mercury orbiter mission produced a theoretical cost reduction of nearly 100 million dollars. The paper examines the application of the ten principles to this case, in order to illustrate their interconnections. The paper makes the case for adopting all ten principles to effect full savings.

Lastly, the paper proposes the use of a theater environment to implement these interactive processes and teams. Advanced computer technology permits further connectivity with the model-driven design approach and suggests a role for supercomputing. The theater environment, model connectivity, and supercomputing will extend present developments into the 21st century, in which collaboration will be mandatory, given the complexity of missions and constraints of cost.

The Need for Assessment

Reduced government spending requires change to the aerospace culture. The major premise of this paper is that the aerospace industry, an organizational system, must better understand its internal dynamics before intervening to change itself further. One purpose of this paper is to propose a model approach for assessing and measuring relevant variables to the change process, as well as explore the inherent difficulties in doing so.

JPL's initial steps to meet the demand for change included training in leadership and introduction of teams and tools within a process-oriented organization. However, JPL made these changes without clearly assessing baseline conditions, the spectrum of relevant change variables, or the impact of each intervention. Though interventions yielded some savings in cost and time, this paper poses an empirical question. Had JPL had a relevant model of change in mind from which a coordinated strategy with management emerged, would a more significant result have been produced earlier?

This paper will describe JPL's experience in the context of a larger model, partially derived from that experience. A secondary premise of this paper is that this model and JPL's experience will be useful to all organizations to the extent that the concepts are sculpted to fit the uniqueness of each system. Cultural and management differences across organizations require individual assessment and strategy implementation within the framework of the model.

General systems theory (e.g., refs. 9, 10), which describes all events as part of a network of interlocking, interdependent systems, provides a conceptual framework within which the content of social and physical sciences can be logically integrated. The theory eliminates rigid discipline boundaries that hide orderly relationships among parts of the real world and thus obscure their shared characteristics. Accordingly, it furnishes precedence for discussion of the interrelationship of organizational processes, of people within teams, of teams within organizations and across interdependent organizations, and interdependence among people, tools, and technology.

Kurt Lewin's force field theory (ref. 2) has significantly influenced the field of organizational development. This theory, which Lewin posited as applicable to all social systems, maintains that equilibrium in any system or organization is reached as the resultant of opposing driving and restraining forces. The system maintains equilibrium in the absence of opposing forces. Thus, identifying and manipulating the field of forces to move the system's equilibrium point in one direction or another can effect change in an organization.

Using Lewin's theory, one can construct diagrams of these forces which created movement to other equilibrium stages during the last 15 years at JPL. These forces are levels of control by management (ref. 11) to change the balanced, equilibrium point to another state. Belief systems (such as credos, mission statements, and visions) are drivers. Boundary systems (such as codes of business conduct, strategic planning, acquisition, and operational guidelines) are restrainers. The important driving and restraining forces are shown in Figure 1.

The time scale is on five-year centers, and approximates major equilibrium or stable points, just prior to change, as JPL responded to a changing environment. Interestingly, this time frame approximates the time needed to initiate and develop an outer planets mission. This time constant is important to understanding how quickly a culture can adapt.

From 1985 to 1990, single missions with multiple payloads (science) dominated exploration. The drivers (beliefs) were science and a single command and control parallel structure (the project office) to control technology and enforce a policy of 'no risk.' This policy evolved from an era of early failures in the space program. The imposed boundary condition to do things cheaper resulted in less costly missions such as Topex. This reduced funding signaled the end of a decade of large missions and spawned the concept of 'Faster, Better, Cheaper' (FBC).

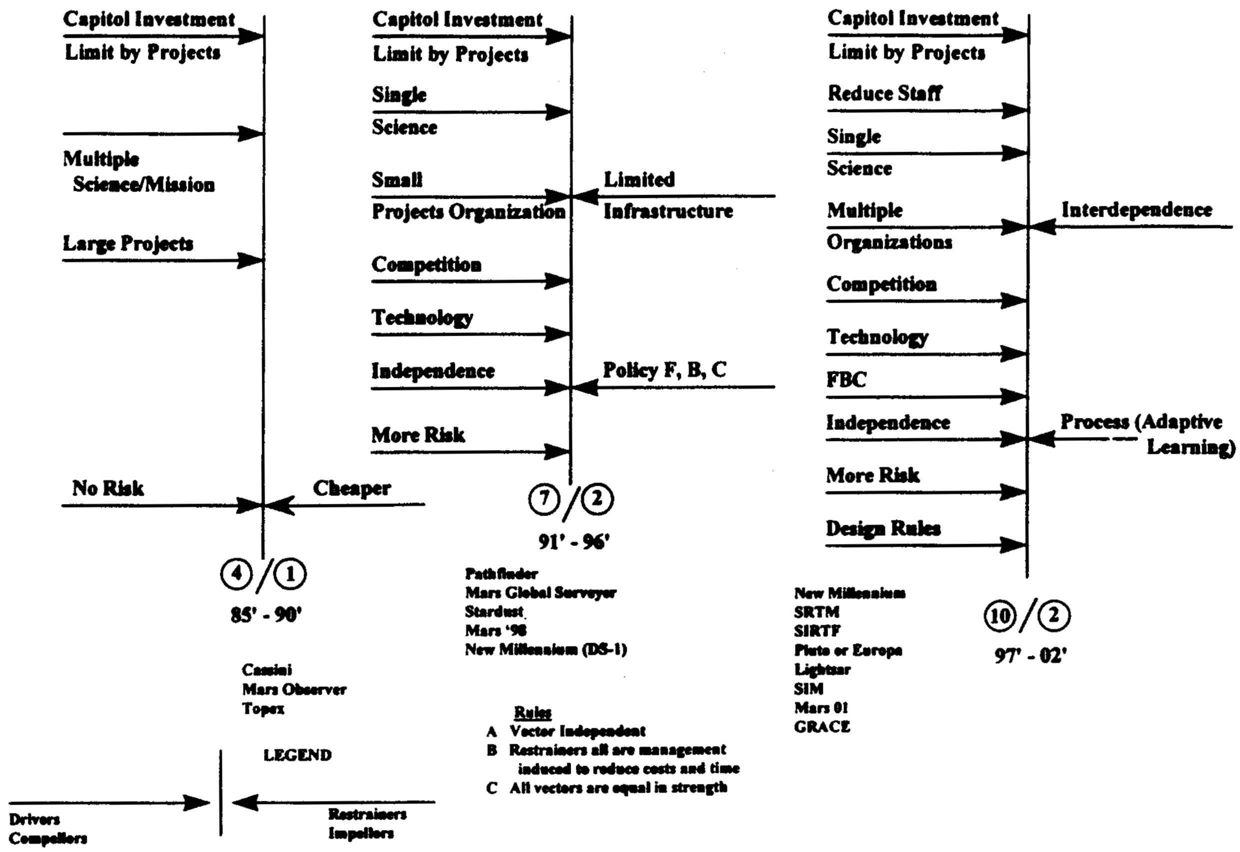

Figure 1. JPL Systems Model

From 1991 to 1996, FBC gained full momentum. The new policy, introduced by Dr. Dan Golden (NASA administrator), actuated a change in management strategy. This, in turn, interjected a new restraining force into the NASA culture (field centers and aerospace industrial partners). The intention of this policy was to modulate the system to be more responsive to the availability of government funding and the public's desire to reduce government spending and balance the budget. Accommodating this new policy, Golden rescinded the 'no risk' policy that dominated development during the previous decade. (For the most recent integration of the FBC policy, see ref. 12)

In addition, two important new drivers emerged. One was the expressed requirement for new technology on each mission, and the other was decentralized control at NASA to promote healthy competition. The introduction of cost-capped programs, requiring competitive bidding, encouraged competition among NASA field centers.

Response to these new policies was not immediate, due to the inherent five-year constant mentioned earlier. Underlying the policy of FBC was the need for interdependence. However, JPL's culture, founded in independence, responded with innovative new ideas in technology and approach to save costs. This force is shown in Figure 2 as the driver, independence. As NASA created cost-capped programs along thematic visions, competition for these missions soared. Thus, the driver for small, multiple parallel organizations emerged as a new market driven paradigm surfaced. These parallel organizations competed for the infrastructure benefits from ongoing larger programs and were independently organized.

The Pathfinder mission, part of the Mars Program, was a prime example of such an independently organized parallel budget of 170 million dollars (ref. 13). At 170 million dollars, Pathfinder was a true bargain. Compared to earlier missions, it represented cost savings of almost 400%.

This success required a new paradigm to sustain a program at these cost levels. The next step for JPL is to glean information from this experience and integrate lessons learned into its culture. Although Pathfinder was imminently successful, without the support to its infrastructure of the larger organization, it could not have become the model for a new environment. Indeed, over the next five years, many smaller missions will emerge, all demanding organizational support to compensate for lower cost of doing business.

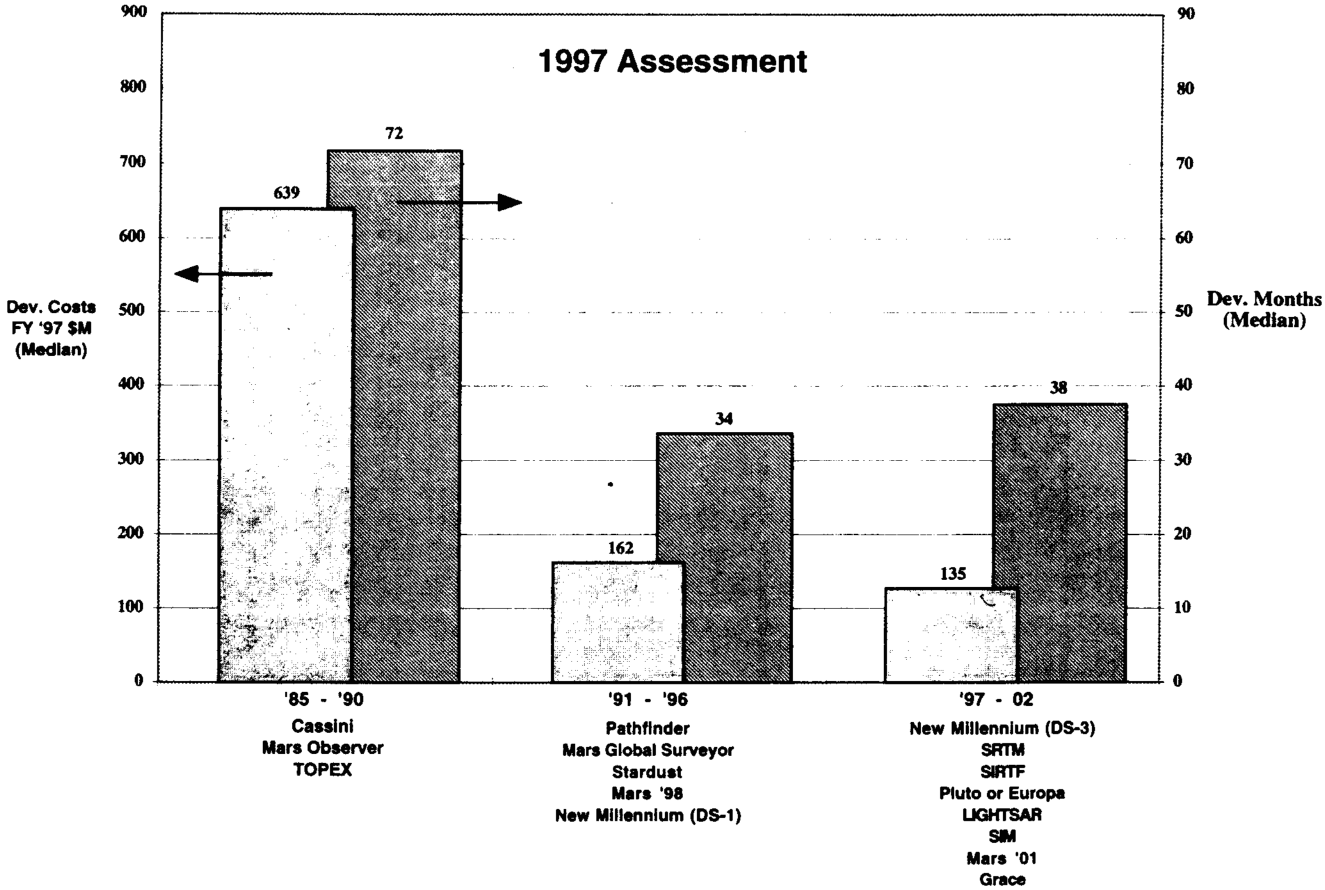

Figure 2. Faster and Cheaper Median Development Costs and Time

As we move into the new millennium (1997 to 2002), new strategic policies will be initiated to lever JPL's system into compliance with the new environment. An important new restraining force, the requirement of interdependence among currently competing projects, is already emerging.

A capped overhead pricing system, which limits institutional support to projects, is stimulating a new policy of interdependence. Presently, there are no fewer than 48 projects competing for precious resources. Interdependence requires collaboration and sharing of facilities and designs.

As Figure 1 illustrates, the restraining policy of FBC becomes fully integrated into the culture and a new paradigm emerges. FBC then becomes a driver.

An important relevant policy change, a restrainer, is currently occurring at JPL. A process-focused approach is being used to integrate FBC into the basic fabric of the culture. Introduction of common processes is promoting adaptive learning (e.g., ref. 14) within the organization. Opposing this intervention is the driver: pressure to maintain an independent approach to meet current challenges. Those preferring this approach view processes and interdependence as constraints to free enterprise.

Thus, as Figure 1 illustrates, JPL can be described as a system of opposing forces. Measurement of how the system behaves, given new forces, before making additional interventions would help determine the appropriate strategy to effect optimal change.

Each NASA management policy is a lever of control (ref. 11) within the organization. These controls must be applied with a strategic plan consistent with the organization's vision and goals in mind. Inconsistency in applying these controls will likely result in failure to meet the organization's objectives.

For example, a lever of control emerged with reintegration of the Cassini team into the JPL culture, following their five-year re-location to develop the mission. During the early 1990's, the force of FBC and competition produced a change in the laboratory's basic development approach. This change was a shift in power from line management to individual projects. As a consequence, the new development process takes substantially more risk. More attention is placed on cheaper and faster than on better. With technology also being a heavy driver, these two forces can produce optimistic performance goals.

When the Cassini culture left in the late 1980's, the pressure to do things better with no additional risk was strong. Presently, FBC and technology oppose this control. After the appropriate cultural reintegration of the Cassini developers, a modulation of faster and cheaper is expected toward better. However, without the proper measurement of the system's taking less risk as a policy, the outcome is less predictable.

A better way to introduce this new control would be first to study the impact of this new policy on a system model and then predict an outcome. This result would modulate the nature and rate of the application of this new force.

A System Model

Using the basic ideas of Lewin's system model, it is useful to construct a simple, linear model that intuitively represents the dynamics of change at JPL. This model will update Lewin's terminology to fit an aerospace system. Lewin's term, 'restraining forces,' will be coined 'impellers' (I). His term, 'driving forces,' will be coined 'compellers' (C).

If one simply equates no change to an equilibrium point with no impelling forces (IF), then linear change can occur only when management takes action to change the stable point to a better one. Opposing change are the compellers. The word 'better' is interpreted in terms of environment (internal and external) and business strategy.

A simple linear model of the time constant for change is directly proportional to the normalized difference of the number of CF's and IF's, where each force is weighted equally, as

$$\tau = \tau_S \cdot \left(\frac{\sum_i^N \left(CF_i - IF_i\right)}{\sum_i^N \left(CF_i\right)} \right) \tag{1}$$

From Equation 1, it is easy to see that with no management intervention, the modifying term of forces is unity and no change occurs.

It can be further assumed that the equilibrium time constant, τ_s (years), itself can be represented linearly as,

$$\tau_s = \tau_{MIN} + \frac{\left(\tau_o - \tau_{MIN}\right)}{M} \cdot \left[M - \sum_i^M \left(R_i\right) \right], \tag{2}$$

where R_i = ratio of the per year investment of burden dollars to burden budget,
M = number of years,

τ_O = product development time (years), and

τ_{MIN} = estimated minimum product time, (years)

An examination of Equation 2 shows that a zero investment program produces no change; $\tau_s = \tau_o$, the development time of the product. With employees all producing a product and with no management intervention, the time constant will not change appreciably.

Therefore, two independent actions change an equilibrium point, management intervention (investment of people and dollars in new tools) or parallel structures.

It is useful to use JPL as an example. In the mid-nineties, the normalized force ratio was 5/7, with two management actions in place forcing a change in equilibrium. A small investment program of roughly 10% per year for three years was initiated. The product development time of an average mission (Figure 6) during that time period was 48 months. Therefore, Equation 1 predicts a time to change of 32 months, slightly less than the investment program of 36 months. The model also shows that with no investment, the IF's would produce a change in 34 months.

The difference between these predictions due to investment is almost insignificant, which points to the limits of investment alone. The actions of management in the form of an impeller produced the larger effect. Both effects act simultaneously to reduce the natural time constant.

The experience of JPL in 1998, after nearly three years, has produced a shift in the equilibrium point to a new stable point. The development time is now roughly 38 months, slightly larger than the 36 months of Pathfinder, and the 33 months of the Mercury Orbiter case.

Referring back to Figure 2, using these new estimates of the constants and a normalized force ratio of 8/10, another investment program of 3 years predicts the time for further change is 36 times 8/10, or 29 months. With no further investment, the time to change is 30 months.

Interestingly, for the normalized force ratio of 5/7, the time to change is 27 months, indicating a more powerful influence of the environment and management resisting further changes.

Though intuitive, this model is not sophisticated. However, it illustrates some salient points. The need for more complex models and the need for empirical data is evident. Such a model, developed for a company, could suggest correct strategies and prudent capital investments. For example, a better model might be a true feedback control model with a plant function. As interventions are made, change occurs with time, and the dynamic system transitions to other states. In this case, it is likely that a greater difference in the investment term will be realized because the effects of investment over time have a compounding effect.

This model illustrates the influence of the compellers. Management can also modulate the compeller side to some degree, as with an introduction of the design rules mentioned earlier, or effect removal of some compellers (ref. 11).

Cost Reduction Possibilities from Process Change

In 1996, the U. S. Navy conducted an important survey which was part of the Joint Strike Fighter Program, aimed at the Manufacturing Affordability Development Program (ref. 5). The survey produced significant results that apply to the problem of changing processes within the aerospace industrial complex. Figure 3, produced from a survey of seventeen aerospace facilities, shows the improvement learning curve, using existing designs, but with improved product techniques and better control at each production stage.

If one fundamentally changes the process with productivity in mind, a shift in the ordinate occurs even for a single production unit. This is precisely the case for single scientific missions. The ordinate shift is on the order of 25-30 percent.

The hope, then, is an expected cost reduction of at least 25 percent for single items and more if one can capitalize on reuse from the initial design. This level of reduction is necessary to maintain the promise of FBC, with no additional risk. To realize these savings requires an understanding of the culture and management structure.

Introduction of technology and new approaches to work force utilization must be part of an overall strategy to effect change. This strategy can be derived from the organization system model and will be unique to the company's culture and management approach.

Aerospace as a Culture

Aerospace organizations can be culturally very different. In order to effect change, Schneider (ref. 6) posited that assessment is crucial to understanding the culture of an organization. He describes four primary cultures – 'command and control,' 'cultivation,' 'collaboration,' and 'competence.'

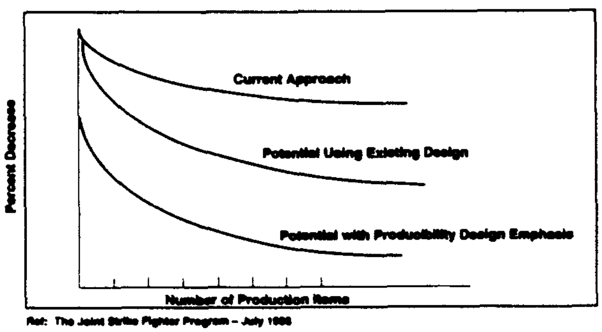

Figure 3. Learning Curve Improvement Potential

JPL's cultural basis is derived from its association with California Institute of Technology and is similar to Schneider's (ref. 6) description of Bell Laboratories' culture. Both are 'competence' cultures and, thus, value individual expertise and focus on achievement. Schneider's analysis of competence-based cultures implies that JPL's leaders would be natural strategists with long-term vision. Indeed, JPL looks to the future and strives to anticipate contingencies relevant to the mission. JPL's emphasis on competence, though vital, is not sufficient to work most effectively toward NASA's vision of discovering life in the universe. As Oliver concluded (ref. 15) in his 1998 INCOSE conference paper, "Teams and Organization, a Model-Based Approach," the combination of cooperation and competition is a powerful basis for organizing business.

JPL's vision is aligned with NASA's. Now we must move ahead at a pace that can only be supported by a more collaborative approach. Therefore, JPL's current challenge is to balance its essentially competence-based culture with an increased value on interdependence and process management.

With the introduction of STS, for example, parallel structures can infuse some of the strengths of a collaborative culture into a competence-based one. An example of this at JPL is the formation of a collaborative team, Team X, a permanent team of experts formed from the various technical disciplines. Team X's interdependence compensated for some of JPL's cultural weaknesses and, thus, adapted to the need for reducing costs.

Team X exists as a permanent structure -- a virtual, horizontal organization that is highly collaborative – within an otherwise vertical organization.

Sociotechnical Parallel Structures

In 1994, JPL engineers recognized the need to reduce cost and time of mission design. In response, JPL built a facility called the PDC, the Product Design Center, which utilizes concurrent design and common tools. In addition, we established a test bed for early prototyping. Though these changes provided greatly needed supporting structures, design time did not drop appreciably.

At that time JPL's system requirement process was document defined and requirements driven. The resultant inherently sequential process limited the impact of the PDC. In addition, over the years each subsystem at JPL had evolved independently to self-sufficiency and, thus, toward devaluation of co-location and its correlated increased communications. Independence produced duplication of tools and stimulated contention within the organization. The organization competed for tasks where boundaries were not well defined. For the PDC to realize its potential, a new parallel process was required.

The introduction of Team X into the PDC met that requirement. Team X executes a standard process for all flight projects during the conceptual study phase. This crucial element of the general process met the demand for quality engineering of new study support, which far exceeded available personnel. JPL produced more than fifty studies during 1996, at a reduced cost of $160,000 per study. The overall $8,000,000 cost reduction translates into a potential production increase amounting to twice the number of studies produced for the same amount of money spent the previous year.

Introduction of Team X, a permanent team of experts, superimposed a collaboration culture on JPL's core competence culture. Because the team experts maintained their permanent location within each technical area, JPL's core culture remained unchanged. Collaboration with Team X created a cross-functional team identity for each participant expert as well. Communication skills and the ability to function within a team environment were selection criteria for Team X members.

To facilitate the new process, some of JPL's cultural notions of expertise had to be addressed. A popular cultural belief encouraged engineers to provide careful, well thought out solutions. Team X sessions require quick, first-order answers. Another popular belief encouraged having a coherent solution before making trade studies, an untenable approach to dealing with cost-capped missions. Team X's approach of iterating cost and performance, then striving for coherence, is faster although non-linear.

Reconciliation of process to individual and organizational value systems requires skillful leadership. Satisfaction of individual, team, and organizational values is linked. Team members' personal value systems blend to form a team value system, which is, ideally, aligned to overall organizational vision and mission. By quickly generating a report to the customer, Team X can immediately realize the satisfaction of making a difference to JPL. Personal rewards and recognition are important factors in sustaining individual and team performance crucial to realization of organizational goals (e.g., ref. 16).

The Ten Principles

A prescription for change within typical competence cultures, like those within the NASA family, includes a blending of teams (people), processes, and tools (the PPT triad). The original paper (ref. 1) suggested new ideas as a paradigm for change. The result of experimenting with these ideas over the last year is their evolution into ten basic principles (See Figure 4).

The first three principles focus on the people aspects of the PPT triad. The first principle emphasizes the importance of leadership skills to the new paradigm (e.g., ref. 17). Managing technical conversations to produce desired results requires new skills, such as listening with an ear and eye to behavioral process. Team facilitators within and across teams manage process by triaging content direction with interpersonal exchange (ref. 18). This requires much more than simply hearing content. It requires the ability to discern *how* the conversational content is delivered and how that influences outcome. The team facilitator uses this behavioral information flow to steer and fine tune interactions in the direction of the meeting's desired outcome (e.g., refs. 19, 20).

Commonly agreed upon leadership characteristics - the ability to see beyond the status quo to a larger vision and purpose, to inspire others to adopt that vision, to model behaviors consistent with the vision, to make available resources to others to enable their progress toward the vision, and to encourage that progress - are necessary but not adequate to the role of the leader in a PPT environment. Crucial is the leader's ability to detect what is needed on a day-to-day basis to most effectively influence others, whether teams or individuals, toward the vision. This requires the ability to correctly discern where people *are*, relative to understanding and implementing the vision, as well as the ability to time and target the level of intervention accordingly. For example, a team may be lagging in meeting objectives because they have lost sight of the vision or because one team member has been derailing process in accord with a personal agenda at odds with the vision. Whether to intervene at all for some period of time in order to allow the team to correct its own process depends upon the leader's assessing the source of the difficulty accurately and knowing the team resources for resolving it independently.

The second principle evolved from the growing necessity for groups of individuals to collaborate in order to address complex objectives. The Team of Teams concept describes groups of cross-functional teams, which work together and,

PEOPLE
1 Leadership
2 Team of Teams
3 Dynamic Continuous Training and Coaching

PROCESSES
4 Redesign processes with value to the customer as the primary metric
5 Dynamic System Engineering
6 Concurrency
7 Model Driven Design
8 Sharing and Reuse of Knowledge
9 Just In Time Availability

TOOLS
10 Dynamic Virtual Manufacturing

Figure 4. Ten Fundamental Principles

thus, form an interdependent second order cross-functional team. This type of system constitutes a powerful synergistic creative force if effectively integrated. Effective teams blend into an overall, dynamic process to create breakthrough concepts (e.g., ref. 21), resolve issues, and reach objectives. The process of Team of Team interactions requires careful crafting and clear team vision, mission, and operating strategy.

Team leaders across teams form a third order team, which synchronizes second order team functioning. Able team leadership in such a process requires training in the behavioral aspects of effective communication. Heirs (ref. 22) addressed the enormity of considering all relevant human variables in a simple team. The complexity of human interactional variables across teams suggests the need for systematic measurement of those thought to be crucially relevant, in order to understand their influence on project outcome, as well as their actual relevance, (ref. 23). Likert scale assessment (ref. 24) using team developed criteria will provide data for future studies. Because the teams' effectiveness powerfully contributes to outcome, an overall facilitator observes their function and offers feedback in real time via earphone. A technology design to support this interaction array will be described in a later section.

The third of the people principles requires continuous training, as the tool set evolves and continuous team building. Training is aimed, first, at optimally interfacing the tool set and its user with the workflow process and, second, re-evolving that optimal interface as the tool set or workflow changes. Teambuilding involves facilitating team process on a regular basis by keeping vision clear and commitment to it strong. It also provides a context for resolution of team process difficulties. An effective teambuilder is skilled in understanding five nuances of communication, identifying differences in personal constructs (e.g., refs. 25-28), and relating these differences to difficulties in team process (e.g., ref. 22). Team participation can provide potent positive or negative impact on team members' motivation, depending upon internal process, (e.g., refs. 29, 30). To enhance potential for creativity and innovation, (e.g., ref. 31), the team environment should contribute to team members' sense of well-being on the job, (ref. 32). Team leaders are trained to strategically pull team members into learning the fundamentals of team facilitation in order to guide the process via their input and, thus, enlist their cooperation with it. Team contribution to shaping the process produces a sense of ownership and empowerment conducive to teamwork (e.g., ref. 33).

Finally, team leaders are trained in processing, organizing and managing the various levels of communication requisite to the Team of Team models. An important aspect of that ongoing training is bootstrapping from their own learning as they experience the Team of Teams process.

Next are six principles to guide design of process development. The fourth principle, including the customer in the process is paramount (ref. 4).

The fifth principle, use of a dynamic system engineering process, prefers a top down system approach to the iterative team/model process design. A bottom up approach alone neglects the top end functional requirements too long and compromises virtual testing.

The next two principles, concurrency and model-driven design, involve an intimate relationship between technology and teams. Cummings and Worley (ref. 7) stated that STS theory has two basic premises. Of interest here is the first, that effective work systems must jointly optimize the relationship between their social and technical parts. In order to effect their integration, it is first necessary to examine the state of readiness of the computational technology and tools, then integrate the social order of teams with the appropriate supporting system.

Computer technology has achieved megabyte clock cycles that enable rapid simulation at every level of design and development. An example at JPL is the Team X special tools conceptual design environment. Spreadsheets projected on large screens provide visual reference as an aid to conversation management by the leader. Simultaneously, the results of each team member's analysis are 'published' for the team's visual inspection.

The best tools are ones that support the conversation, rather than the analysis. Sophisticated analysis tools, available to each team member, operate in the background to support the main activity.

Following the conceptual design phase, more detailed design issues emerge. These call for complex discussions requiring simulation analysis and, therefore, more insight into the relationships between technical components over mission time. Please see Figure 5 for a matrix of simulation tools over different project phases. The simulations relate to each other by process. Figure 6 shows a grouping of the major simulation tools by the MSD and DBAT processes. The VIVO process integrates and tests the ensemble.

Each process contains subsystem objects, and each object can be decomposed into fundamental objects within CAD tools. Each object is a nested waterfall of design, development and test. Requirements are maintained only at the highest level. The design itself of the lower objects contain the requirements in the design. (ref. 3).

Computational technology supports these activities in two distinct ways. First, it provides object models to create a virtual environment that captures, verifies, and even tests interactions. These models are found within the MSD process. Second, it tests and verifies the logical designs of circuits and software prior to hardware and software

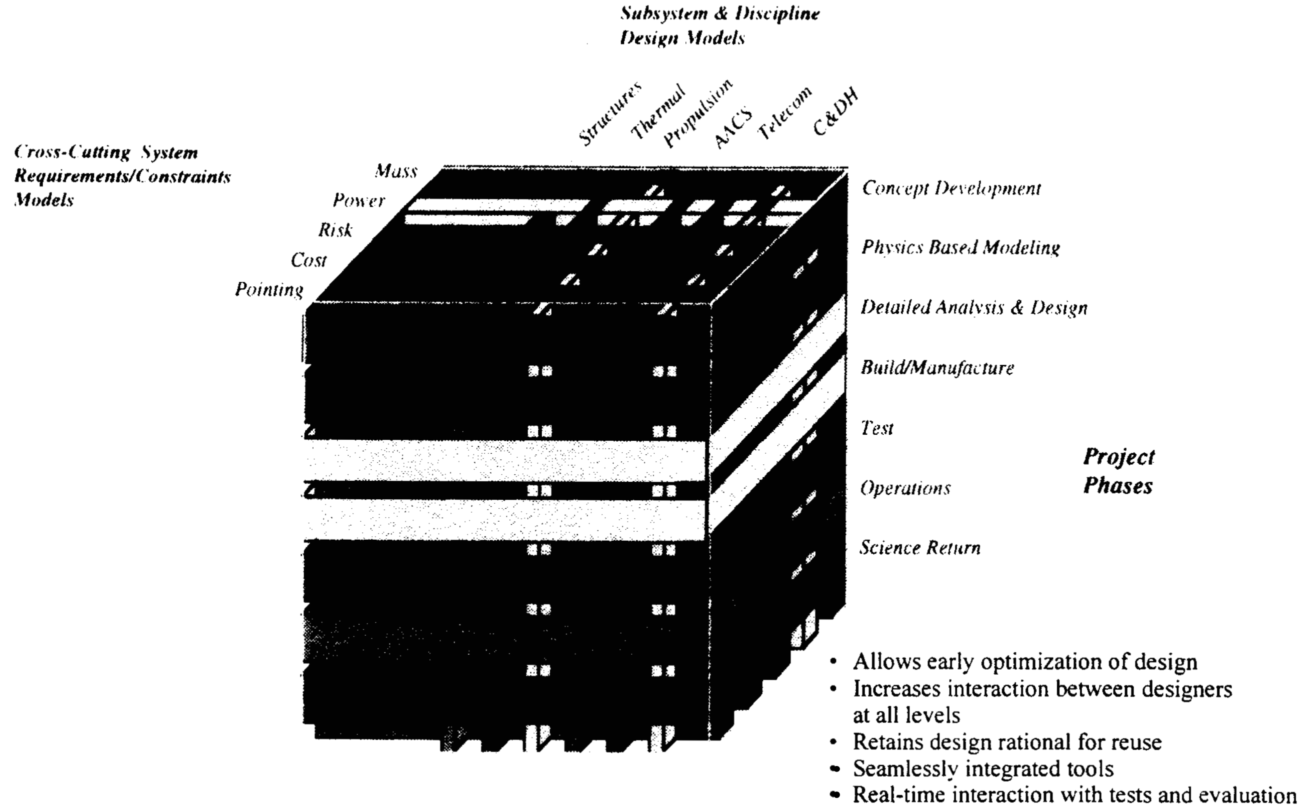

Figure 5. Intelligent Simulation Based Design (ISBD)

production. Abid et al (ref. 34) referred to this as 'hardware/software co-design for embedded systems.' These kinds of models are contained within DBAT.

Recently at JPL, Edward H. Kopf took a practical, flight-qualified design through the co-design process, beginning with i-logic's Statemate (development tool) to a Flight Programmable Gate Array (FPGA). The constraints of flight qualification and reliability for NASA's X-33 increased the difficulty ten fold. To avoid confusing the synthesis tools and producing unnecessarily complex hardware, he designed a simplified instruction set, a breakthrough to developing qualified hardware/software design.

Co-design begins with detailed design, captured by behavior models, and extends to CAD systems. Connecting this process to other kinds of virtual models creates a top down virtual manufacturing system of objects which are reassembled by the VIVO process.

Wall (ref. 35) described JPL's implementation of modeling system requirements for space missions. This paper is unique in its complete description of a 'Top Down' system design process which creates, corrects dialogues on technical issues, and uses the technology to manage the information flow.

Combining these two model types with a team approach enables integration of teams, processes, and tools. Figure 7 describes generic team conversations across design processes. First, Team A (designated Team X at JPL) constructs self-verifying requirements models (ref. 36). Technical conversations include performance evaluations and critical design trade-offs. If the design parameters, p, exceed the requirements, P, Team A decides whether to alter requirements, P, or flight sequences, S. For this level of conversational / model environment to work, models must be kept simple and distinct. Barbieri and Estabrook (ref. 37) reported that a simple model (Nuthena's Foresight tool) can be constructed in about one month. A larger, more sophisticated version of 30 Mbytes was not useful and took six (6) months to complete.

Team B constructs detailed object design models (object models themselves are DBAT processes), checks for and evaluates requirements incoherence, and reports their subsystem recommendations to Team A. Team A either accepts Team B's recommendations, changes the requirements, or changes the flight sequence (often with a science descope). The margin of available resources determines whether alternative design suggestions are used.

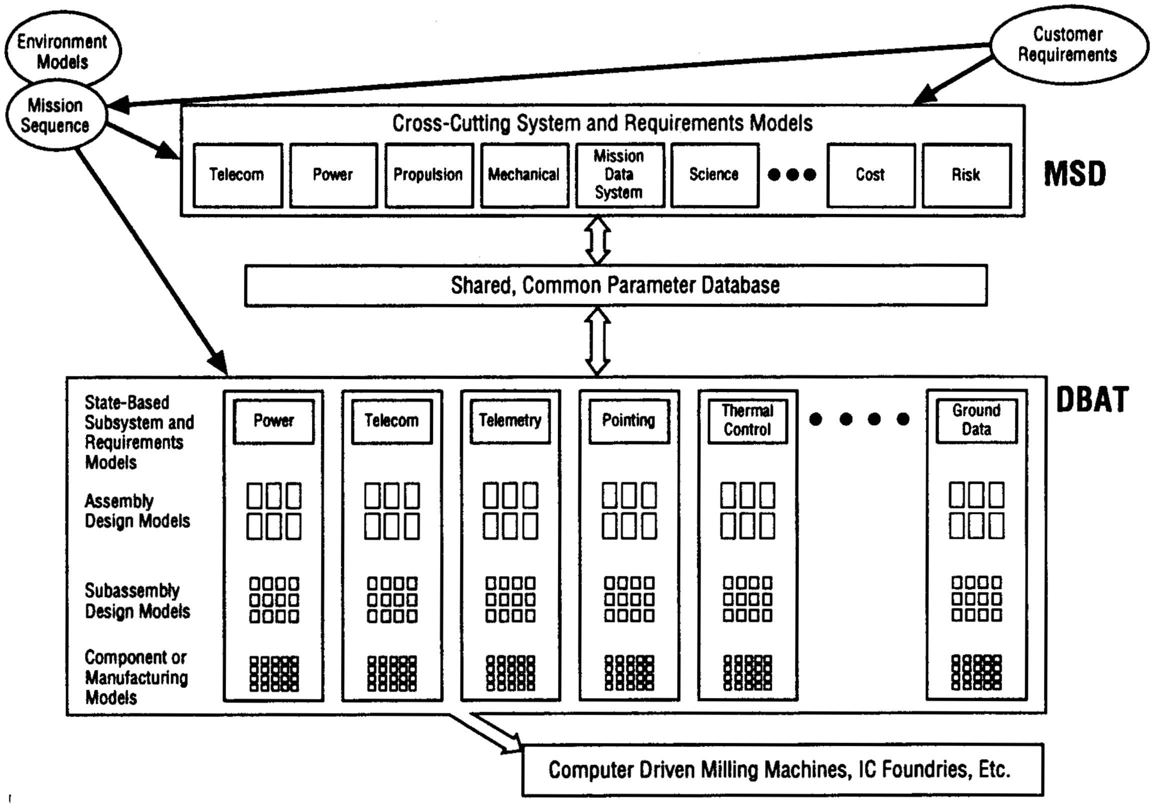

Figure 6. Model Architecture

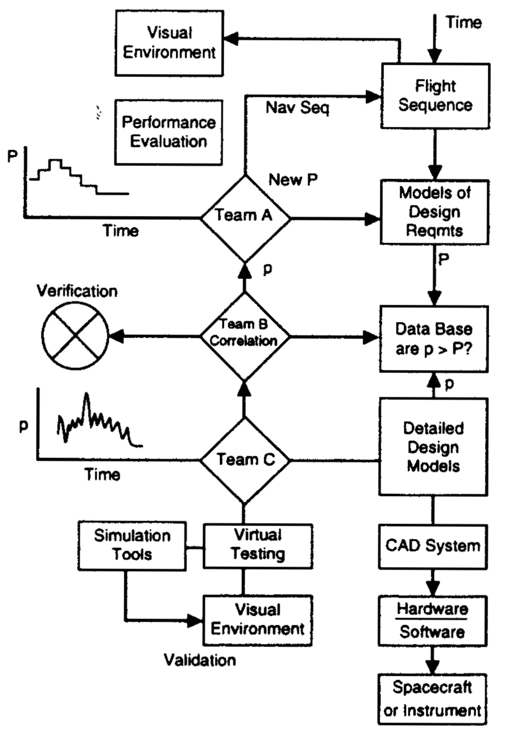

Figure 7. Team Conversations versus Design Process

Team C initially engages with model object testing, then tests actual hardware and software. Team C also uncovers requirements incoherence. After test evaluations, they report their results to Team B. If results are unexpected, Team B & C attempt to clarify the issues before reporting to Team A. In this system, data flows from top to bottom, from upper level models to designs, and information returns through a sequence of interacting Teams A, B, and C.

Team A adopts the role of direction and, thus, decides on the correct course, given Project commitments. Team B provides design possibilities, and Team C evaluates the results. All teams provide input necessary to iterate the design toward hardware and software maturity.

Thus, the innovation is a model driven system designed for compatible interface with teams. The models themselves provide documentation of the design and faster information exchange. These models, with their carefully designed object relationships, provide the tool counterpart to relationships among teams.

This is very different from the usual model approach, which is to design large models relating physics to operation. Careful object design to enable meaningful conversation among people requires simple distinctions about the models' intended use. For example, a resources or requirements model is different from a physics model, which is, in turn, different from an object design model.

The eighth principle requires a proper system to capture information and make it available to everyone. A good information system that shares and reuses knowledge, though necessary, cannot replace a well-designed concurrent process that converges in a stable manner. Process efficiencies are enhanced when knowledge is captured and made useful to others who are executing the same process, but beginning later.

The principle related to process design, the ninth, states that, to 'go fast,' parts or raw material for parts must be made available at just the right time. This can be accomplished through strategic alliances among industrial partners. JPL's approach assures suppliers a steadfast customer over the next decade.

The tenth principle relates models as objects to each other to achieve a virtual manufacturing system. The current state of computer technology necessitates distinctions between models, in order to preserve the simplicity of the process. An Oracle database contains information required by the models and, thus, avoids expensive interface design between models.

Analytical Study

If processes are designed with these principles in mind then the cost reductions in the 20-30 percent range should be expected.

A typical mission to orbit Mercury is discussed as an example of an analytic evaluation. This study compared the efficiencies in cost and schedule of the waterfall approach, as opposed to the model driven design approach. JPL's team of experts, Team X, evaluated the mission conceptually. Using the existing design approach without reengineering and with the sequential NASA phases A, B, C, D and E, Team X designed and costed the mission. Conceptual design, phase A, matured to confirmation after requirements definition, phase B. Phases C and D - design, build and tool – were followed by phase E, the operational phase.

Team X estimated the development time to be 48 months. This time frame is consistent with the average mission duration shown in Figure 8.

Figure 9 depicts the estimate in 1997 dollars for the entire mission. Total mission costs are about 357 million dollars with reserves. Note that the launch vehicle costs are regarded as fixed at 54 million.

Then, the new modified object development process, using model-driven design, was introduced to the team. After being trained in the new method, Team X used it to re-cost this mission. Their analysis assumed that the institution supplied tools and test facilities as part of the infrastructure.

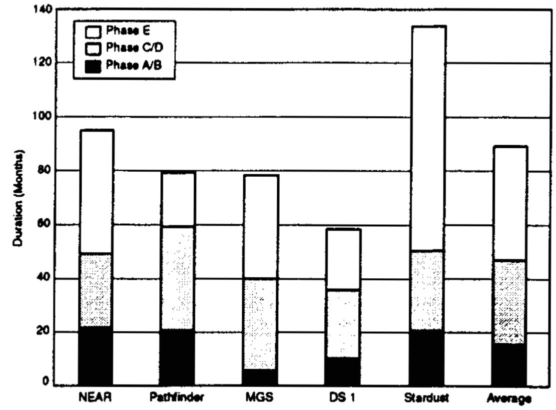

Figure 8. Flight Mission Metrics - "Faster"

To meet the demand of FBC, phases A and B were combined. Using this A/B period to conceptually develop the mission and capture the requirements involved producing the system level requirements models. The new process took only nine months to completion of phase A/B, and phase C/D was shortened to 24 months. The overall 48 months using the waterfall method was reduced to 33 months. In addition, the model based spiral approach reduced cost to 262 million, a savings of about 95 million dollars, or roughly 27 percent. This costing excludes the fixed cost of the launch vehicle and is consistent with the earlier predictions.

Mercury Orbiter Case ('97 Dollars)

	Team X Waterfall Estimate	JPL Process Estimate	JPL Next Mission
Project Management	11.4	5.3	5.3
Science	2.0	1.8	1.8
Project and Mission Engineering	4.1	2.5	2.5
Payload	38.3	34.4	34.4
Spacecraft	112.1	93.2	53.6
ATLO	22.3	5.3	5.3
Mission Ops Design	8.9	9.7	9.7
Mission:			
Phases A/B	32.1	0.0	0.0
Reserves	46.2	30.4	22.5
Launch Vehicle	54	54	54
Mission Operations	26.0	26.0	26.0
Total	357.0	262.0	215.0

Figure 9. Analytical Mission Study: Mercury Orbiter

The Triad of the Future

As missions become more complex and resources more constrictive, no single infrastructure can sustain the state of preparedness needed for unilateral development of a mission. Collaboration with each other is necessary to accomplish the complex goals NASA envisions. Every NASA organization is engaged in the process of achieving this level of teamwork.

How to work effectively together in the future is yet to be determined, but NASA is committed to this outcome. Goldin's ISE (Intelligent Synthesis Environment) Program honors this commitment. Included in this program are activities that address cultural change. Although we are still learning about cultural change, application of the ten principles can produce substantial savings. Technology supports this application as we move the culture toward more collaboration.

Collaboration in mission development requires access to current design information in a paradigm where that information is changing rapidly. The object model driven approach used at JPL is fundamental to support such a paradigm. Since objects are self-contained units, concurrency with cross-functional teams is possible. The model-driven design approach incorporates a data base solely for the purpose of iterating the top level objects, with the fractal lower level objects. Its primary purpose is to promote technical conversations by uncovering incoherence between requirements and design.

The current ISE Program is developing the concepts for increasing collaboration between organizations and/or teams within organizations. As we extend the concept of parallel structures and teams across organizational boundaries, the necessity for scripting team sessions is becoming obvious. Scripting is necessary to synchronize the different paces of the teams as they work. Each pace is culturally unique to the team's organization and must be respected to promote cooperation. However, the scripting process between teams creates dissonance, resulting in teams with slower paces speeding up and teams with faster paces slowing down. Scripting the process yields a composite of a natural pace with a richer technical solution.

During a session, scripts are followed to produce the desired result. A script might first identify major issues resulting from alternative design approaches or from out of tolerance specifications. Whatever the cause, teams or sub-teams will resolve issues concurrently and publish the results to everyone via large theaters. The theater presentation brings together the design for review and sets the stage for the next iteration of matching models.

The process to support these turns requires new roles. One role is the information manager, who monitors the production of information and manages the content and flow. Information quality and reliability is crucial to the successful outcome of this process. Special monitoring systems must be designed and developed to meet the complexity of future audio-visual information triage systems.

Lastly, because the design process is reduced to a sequence of connected conversations, the role of the leader as a facilitator or conversation manager is crucial. Supporting the leader as a communications director whose job is to connect the communications so the appropriate conversations occur. Conversations between sub-teams utilize sub-networks of audio and visual technology. The director creates the sub-networks using commercial protocols and networking software applications available in modern day communication links.

These new roles will evolve as the Triad develops to include many cross functional teams. New technology may one day replace these roles, but it is unlikely over the next five (5) years.

Summary

We have entered an era of change, an era which demands that we respond to increasingly complex questions with faster production of better products at lower cost. This challenge requires a new approach. This paper presents concepts essential to this new approach.

Ten fundamental principles, which provide the basis for the new approach are discussed. In addition, two key ideas are developed from a systems viewpoint. The first is the decomposition of a mission into objects, which are building blocks. These objects are concurrently designed, developed and tested within a process of Design, Assemble, Build, and Test (DBAT). The second idea entails an iterative system design process, which uses information about incoherence between objects to resolve design issues. These two ideas use the ten principles in a new systems approach, different from spiral methodology.

Developing this system into a working method in a process-centered organization is the challenge facing many aerospace cultures. Meeting this challenge requires baseline assessments and ongoing measurements to evaluate the development of the systems triad - People, Process, and Tools. Collaboration across NASA and sharing the basic building blocks, the objects, is a suggested new strategy that would help meet the current demand for Faster, Better, Cheaper.

Acknowledgments

The work described was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration. This paper is presented at the 5th International Workshop on Simulation for European Space Programmes, SESP '98, November 3-5, 1998, ESTEC, Noordwijk, The Netherlands.

The authors further acknowledge the contributions to the ten principles by Dr. Ivan Rosenburg, Frontier Associates, on contract to Jet Propulsion Laboratory.

References

1. Smith, D.B. 1997. *Reengineering Space Projects.* Computer Tools, Systems Engineering and Competitiveness Conference. Paris
2. Lewin, K. 1951. *Field Theory and Social Science.* Harpers Business Review. New York.
3. Taylor, D.A. 1995. *Business Engineering with Object Technology.* John Wiley & Sons, Inc. New York.
4. Hammer. M. 1996. *Beyond Reengineering.* Harper Business. New York
5. Ruffa, S. 1996. *A Structured Approach for Rapid Improved Affordability.* Joint Strike Fighter Program. Virginia
6. Schneider, W.E. 1994. *The Reengineering Alternative.* McGraw-Hill. New York.
7. Cummings, T.G. and Worley, C.G. 1993. *Organization Development and Change.* West Publishing Co. Minneapolis, Minnesota.
8. Bushe, G.R. and Shani, A.B. 1991. *Parallel Learning Structures.* Addison-Wesley. Reading, Massachusetts.
9. von Bertalanffy, L. 1968a. *General Systems Theory.* Braziller. New York.
10. von Bertalanffy, L. 1968b. *Organismic Psychology and Systems Theory.* Clark University Press. Worchester, Massachusetts.
11. Simons, R. 1995. *Levers of Control. How Managers Use Innovative Control Systems to Drive Strategic Renewal.* Harvard Business School Press. Boston, Massachusetts.
12. Goldin, D. 1998. *NASA Strategic Plan.* NASA Policy Directive 1000.1.Washington, D.C.
13. Muirhead, B. 1998. *The Mars Pathfinder Approach to FBC.* Prilchett & Associates, Inc. Dallas
14. Jankowicz, D. 1998. *From Learning Organizations to Adaptive Organizations.* MS submitted for publication.
15. Oliver, D.W. 1998. *Teams and Organizations - A Model-Based Approach.* Proceedings of Eighth Annual International Symposium of INCOSE. Vancouver.
16. Cranny, C.J., Smith, P.C., and Stone, E.F. 1992. *Job Satisfaction: How People Feel About Their Jobs and How It Affects Their Performance.* Lexington Books (Macmillan). New York.
17. Hesselbein, F., Goldsmith, M., and Beckhard, R. (eds.). 1966. *The Leader of the Future: New Visions, Strategies, and Practices for the Next Era.* Jossey-Bass. San Francisco.
18. Mischel, W. 1973. *Toward a Cognitive Social Learning Reconceptualization of Personality. Psychological Review,* 80, 252-283.
19. Argyris, C. 1970. *Intervention Theory and Method.* Addison-Wesley. Reading, Massachusetts.
20. Argyris, C. Putnam, R., and Smith, D.M. 1985. *Action Research.* Jossey-Bass. San Francisco.
21. Hayes, J.R. 1989. *Cognitive Processes in Creative Acts.* In Leavitt, H.J., Pondy, L.R., and Boje, D.M. (eds.), *Readings in Managerial Psychology (4th Ed.).* University of Chicago Press. Chicago and London.
22. Heirs, B. 1987. *The Professional Decision Thinker.* Sidgwick & Jackson. Great Britain.
23. Likert, R. 1961. *New Pattern of Management.* McGraw-Hill. New York.
24. Likert, R. and Likert, J.G. 1976. *New Ways of Managing Conflict.* McGraw-Hill. New York.
25. Kelly, G.A. 1970. *A Summary Statement of a Cognitively-Oriented Comprehensive Theory of Behavior.* In Mancuso, J.C. (ed.), *Readings for a Cognitive Theory of Personality.* Holt, Rinehart, Winston, Inc. New York.
26. Kelly, G.A. 1955. *The Psychology of Personal Constructs (2 vols.).* Norton. New York.
27. Beck, A.T. 1984. *Cognitive Approaches to Stress.* In Lehrer, C. and Woolfolk, R.L. (eds.), *Clinical Guide to Stress Management.* Guilford Press. New York..
28. Mahoney, M.J. 1984. *Behaviorism, Cognitivism and Human Change Processes.* In Reda, MA. and Mahoney, J.J. (eds.), *Cognitive Psycho-Therapies: Recent Developments in Theory, Research, and Practice.* Ballinger. Cambridge, Massachusetts.
29. Festinger, L. 1957. *A Theory of Cognitive Dissonance.* Row, Peterson. Evanston, Illinois
30. Nadler, D.A. and Lawler, E.E.. 1989. *Motivation: A Diagnostic Approach.* In Leavitt et. al. *Readings in Managerial Psychology (4th Ed.).* University of Chicago Press. Chicago and London.
31. Anderson, N. and West, M.A. 1998. *Measuring Climate for Work Group Innovation : Development and Validation of the Team Climate Inventory.* J of Organizational Behavior, 19, 235-258.
32. James, L.R. and James, L.A. *Psychological Climate and Affect. Test of a Hierarchical Dynamics Model.*
33. Argyris, C., 1964. *Integrating the Individual and the Organization.* Wiley. New York.
34. Abid, M., Ben Ismail, T., Changuel, A., Valderrama, C.A., Romdhani M., Marchioro, G.F., Daveau, J.M., and Jerraya, A.A. 1998. *Hardware/Software Co-Design Methodology for Design of Embedded Systems.* In Adeli, H. (ed.). *Integrated Computer-Aided Engineering,* 5/1, 69-83.
35. Wall, S. 1998. *Implementation of System Requirements Models for Space Missions.* Proceedings of Eighth International Symposium of INCOSE. Vancouver.
36. Baker, L. 1997. *Foundational Concepts for Model Driven System Design.* INCOSE Model Driven Systems Design Working Group.
37. Barbieri, A.J. and Estabrook, P. 1997. *System Models to Reduce Mission Design Time and Manage Risk: The Mars Microprobe Mission Case Study.* 12th AIAA/USU Conference on Small Satellites.